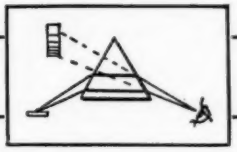
Journal of the

OPTICAL SOCIETY *of* AMERICA

VOLUME 24
No. 1



JANUARY
1934

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Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
11 East 38th Street, New York, N. Y.
FOR AND UNDER THE EDITORIAL SUPERVISION OF
THE OPTICAL SOCIETY OF AMERICA

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Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 24 JANUARY, 1934 NUMBER 1

Optical Rotation of Unpolarized Light

ALEXANDER LANGSDORF, JR., AND LEE A. DUBRIDGE, *Washington University, St. Louis, Missouri*

(Received October 9, 1933)

The question as to what happens to a beam of unpolarized light in passing through an optically active medium does not seem to have been given a definite answer. If such a beam can be regarded as made up of a large number of elementary components, each plane polarized, then each component should suffer a rotation. Consequently, if an unpolarized beam is separated into two parts and one passed through a dextro- and the other through a laevo-rotary solution, such that the sum of the rotations is 90°, the emergent beams should be incapable of interference. With the use of a Fresnel bi-prism it was found that the interference fringes disappeared when the optically active solutions were in place. They reappeared when the field of view was examined with a quarter-wave plate, showing the existence of circularly polarized light as expected.

INTRODUCTION

IT is well known that when a beam of plane polarized light passes through an optically active medium, such as a sugar solution, the plane of polarization is rotated through an angle whose magnitude depends on the nature of the medium and the length of path through it. There seems to have been no attempt, however, to determine whether an optically active substance has any effect on unpolarized light. Whether any effect would be expected depends on the view we adopt as to the nature of an unpolarized light beam. Let us regard it as made up of a large number of elementary components (photons?), each emanating from an individual atom or molecule in the source and each being plane polarized, the polarization planes for the various components having a random distribution about the axis of the main beam. Then, in passing through a sugar solution, each component should be rotated by the same amount but the random orientation would remain. Obviously this rotation would not be detected by ordinary methods. But if we produce some sort of interference phenomenon, e.g., by means of a Fresnel bi-prism, the rotation of the individual components might come into play for interference can take place only between parts of the same component (photon?), since separate components, coming from the same source but from different atoms, would not be coherent. It is the purpose of this paper to describe an interference experiment in which the optical rotation of the individual components of an unpolarized beam was directly observed.

Experiments of this type must certainly have been performed previously, though we have found no account of them, nor have we found any statement in the standard treatises on optics which would enable us to predict with certainty what the result of the experiment would be. In any case we believe the experiment gives such a good illustration of some of the properties of polarized light that a brief description of it will

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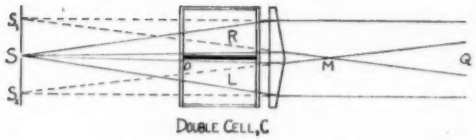

FIG. 1.

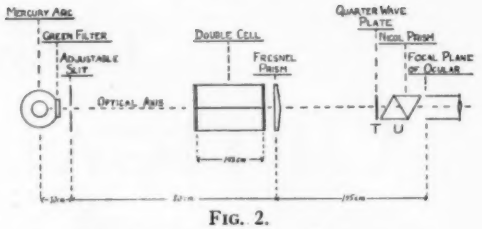

FIG. 2.

at least be of interest to teachers of advanced courses in optics.

GENERAL STATEMENT

If unpolarized monochromatic light from a narrow slit S, Fig. 1, is passed through a Fresnel bi-prism the effect is the same as though the emergent beams emanated from the two slit images, S_1 and S_2, and interference fringes may be observed in the usual way by means of an eyepiece at Q. Suppose now that before entering the prism the unpolarized light is made to pass through a double cell, C, one side of the cell, R, being filled with a dextro-rotary and the other side, L, with a laevo-rotary sugar solution. Let the plane of the partition separating the two compartments of the cell be placed parallel to the refracting edge of the prism and the cell so aligned that all the light from the virtual slit S_1 passes through R while light from S_2 passes through L. Suppose further that the concentrations of the solutions and the length of the cell are so adjusted that if the solution in R rotates a plane polarized beam through the angle θ the solution in L will produce a rotation of $(90-\theta)$ in the other direction. Then, on emergence, the angle between the polarization planes of the two beams will be 90° and the two beams would be incapable of destructive interference. If this is true for any elementary component of the original unpolarized beam it will be true for all and no interference fringes should be observable. To test this conclusion the apparatus was set up as shown in Fig. 1 and adjusted so that without the cell the fringes were clearly visible. When the cell was inserted it was found, after careful alignment had been made, that no fringes could be found in any part of the field, though they at once reappeared when the cell was removed.

This simple experiment would, of course, be inconclusive, for the disappearance of the fringes might be attributed to improper alignment of the system, the unequal optical paths in the solutions or other causes, although careful precautions were taken against these obvious sources of trouble. There is a very interesting extension of the experiment, however, which at once eliminates such interpretations. This extension is made possible by the fact that two coherent beams of light, polarized at 90° to each other, will, if their phase difference is also 90° and the intensities equal, combine to produce circularly polarized light. Now the time-phase relation between the beams from S_1 and S_2 varies continuously in going across the illuminated field at Q. Hence there will be certain positions in the field where the phase difference is 90° and each elementary component will produce circularly polarized light. Hence all the light reaching these positions will be circularly polarized and may be analyzed with a quarter-wave plate (or Babinet compensator) and a nicol prism. If such an analyzing system is placed as shown in Fig. 2 and the nicol properly adjusted, the positions where the light is circularly polarized in one sense should appear dark, while intermediate positions, where it is circularly polarized in the opposite sense or elliptically polarized, will be bright. In other words a fringe system should now appear with a fringe separation equal to that found in the original experiment without the double cell. This is precisely what was observed and a careful study of the phenomena verified every aspect of the theory.

The equations for the intensity distribution in the fringe system may be figured by straightforward methods[1] by computing the intensity for each component and summing for the whole beam. If θ is the angle between the planes of polarization of the two beams and φ the time-phase angle between them at any point in the field of view, the observed intensity I at that point should be given by

$$I = I_0(1+\cos\theta\cos\varphi),$$

[1] See for example, P. Drude, *The Theory of Optics*, p. 250.

I_0 being the incident intensity. For $\theta=0$ (no sugar solutions) we obtain the usual expression for the intensity distribution in the fringe system. For $\theta=\pi/2$ the field should be uniformly illuminated, as observed. When the quarter-wave plate and nicol analyzer are in position the intensity observed is given by

$$I_1=I_0(1+\cos(\varphi\pm\theta)),$$

the choice of sign depending on the position of the analyzer. For $\theta=\pi/2$, $I_1=I_0(1\pm\sin\varphi)$ and the fringes have the same width as when viewed directly but are displaced by a quarter fringe-width. Furthermore, in the two analyzing positions of the nicol, the bright and dark fringes are interchanged. This is what was observed.

Experimental Details

1. The double cell

The double cell was constructed by soldering a thin sheet of brass inside a brass tube 14.3 cm long and about 5 cm in diameter, taking care to keep the sheet plane and parallel to the axis of the tube. A hole was drilled in each compartment of the cell to allow filling with sugar solution and the inside of the cell was paraffined to avoid discoloring the solutions with copper salts. The ends of the cell were ground parallel and glass plates (microscope slides) cemented on with Duco cement. It required particular care to make a liquid-tight joint between the glass and the thin central diaphragm and at the same time to use no excess of cement. It is important to keep the obstruction caused by the cement as small as possible.

2. The sugar solutions

The concentration necessary for the solutions may be computed from data found in the *International Critical Tables*, with the conditions that the sum of the absolute magnitudes of the rotations of the two solutions is to be 90° and the concentration is to be the same for both solutions.[2] The sugar solutions when first made are likely to be colored by impurities; in fact, at the high concentrations used they were often quite opaque. However, by the repeated use of de-colorizing charcoal the solutions can be made perfectly clear. As much as fifty percent of the sugar may be adsorbed by the charcoal and this must be allowed for when judging the initial quantities. If it is necessary to concentrate the solutions by evaporation, care is needed to avoid coloring by burning. Final tests of the rotation of each solution were made in a polarimeter.

[2] The absolute necessity of equal concentrations (thus equal refractive indices) has not been experimentally determined but seems desirable.

3. Adjustment

To line up the double cell with the Fresnel prism and slit, it is convenient to place a simple obstruction (like a strip of paper on a piece of glass) slightly wider than the obstruction produced by the diaphragm and cement of the double cell, near the Fresnel prism, in front of the vertex of the prism. By sighting, one adjusts the apparatus until both slit images can be seen, one on each side of the obstruction. Having thus found a place which receives light from both slit images, one can observe the interference fringes by using an eyepiece. The fringes lie partly or wholly inside the shadow of the obstruction. The obstruction also produces diffraction fringes, but these are easily distinguishable.

The next step is to place the double cell behind the obstruction so that the diaphragm is hidden by it. The two slit images are now seen through the different solutions. By using an eye lens the presence or absence of interference fringes may be determined. The obstruction has now served its purpose and may be removed.

A complete diagram of the optical system is shown in Fig. 2. The slit, cell and bi-prism were mounted on a good optical bench of the type used for interference experiments. The eyepiece and analyzing system, however, had to be mounted separately since the bench was not sufficiently long and if the eyepiece is brought closer in, it is no longer possible to see both slit images through the double cell because of the partition.

An obvious improvement of the experiment would be to use two quartz plates, one right and one left-handed, in place of the sugar solutions. The preparation of clear solutions of proper concentration is most tedious. They were used only because quartz plates of the proper thickness were not available.

Note on Preceding Paper by Langsdorf and DuBridge

R. W. Wood, *The Johns Hopkins University*
(Received November 4, 1933)

THE previous communication is of interest as drawing attention to the experimental evidence of the presence in ordinary light of plane polarized components of random and changing orientation, as was demonstrated in 1864 by Stefan, whose ingenious experiment appears to be not very generally known.[1] He used a simpler method of showing the rotation of the polarized components, placing a quartz plate 5 mm thick, cut perpendicular to the axis, over one-half of the collimator of a 3-prism spectrograph. With a glass plate of similar thickness he obtained several thousand interference fringes in the continuous spectrum of a white source. These were evidently "Talbot fringes" (discovered in 1837) though he does not so designate them. With the quartz plate the fringes disappeared in the orange region of the spectrum, this being the region for which the quartz plate gave a rotation of 90°. Employing circularly polarized light for the illumination, the fringes were distinct throughout the entire spectrum.

[1] Stefan, Sitz. Ber. Wien. Akad. 50, 380 (1864).

Seeing in Sodium-Vapor Light

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(Received October 20, 1933)

RECENT developments in the production of light by vapor lamps have emphasized the need for further research upon spectral quality of light as a factor in seeing. It is evident from a consideration of existing data that, although much is known concerning the influence of spectral quality of light upon the photosensory processes, much remains unknown or at least unformulated concerning the importance of this factor in the world of practice where human beings are functioning as human seeing-machines. The purposes of this paper are to present new data pertaining to the influence of spectral quality of light upon seeing and to interpret the data from the viewpoint of seeing as a universal human activity.

Fundamental Considerations

The only inherent characteristic or property of light is spectral quality. The inherent characteristics of vision are the sensations of brightness and color and from these arises the perception of form. These considerations serve to orient the factor of spectral quality of light in the activity of seeing—which is a partnership of light and sight. In Nature the environment of color is a result of alterations in the quality of daylight by the reflecting and transmitting characteristics of various media. In an artificially lighted world, radically different environments of color and color-contrasts may be produced by illuminants of various spectral qualities. Hence, an appraisal of the influence of quality of light may require interpretations which vary from the narrowest viewpoint of retinal stimulation to the broadest viewpoint of an environment in which human beings must live.

The science of lighting for seeing involves the control of the primary factors of quantity, spectral quality and distribution of light. Many of our previous papers[1] have emphasized quantity of light as the most important controllable factor in seeing. This conclusion is justifiable as long as levels of illumination are generally far below the minimum required for good seeing and adequate conservation of human resources. The exceptions are chiefly those cases of seeing where an accurate or standard discrimination of color is essential and the rare cases where the eyes are hypersensitive to light of certain spectral qualities due to certain pathological conditions. With the development of high-efficiency vapor lamps, spectral quality of light becomes a more significant factor. It is necessary to appraise the visual effectiveness of the light from such sources in order to determine whether or not a greater luminous efficiency with an unusual or unnatural spectral quality is a real advantage. There is also the possibility that the spectral quality of the light from certain lamps may be inherently superior to the light from tungsten filaments, even when appraised upon a basis of equal quantities of light.

Illuminants

Natural daylight and light from tungsten filaments, mercury vapor and sodium vapor are representative for researches in seeing as well as for practical application. There is also the possibility of combinations of these sources for the purpose of obtaining light of other specific spectral qualities. In addition, the light from tungsten filaments may be altered in spectral quality by means of a wide variety of selective filters. Since an adequate appraisal of the influence of spectral quality of light upon seeing involves many phases of the physical and

[1] M. Luckiesh and Frank K. Moss, *Seeing—A Partnership of Lighting and Vision*, Williams and Wilkins Co., Baltimore, 1931; M. Luckiesh and Frank K. Moss, *Recommended Footcandles*, Trans. I. E. S. **26**, 1061 (1931).

biological sciences, it is not within the scope of this paper to present specific discussions on each phase of seeing for each of the many light-sources available.

The usual research technique in the realm of physiological optics involves various methods of comparison rather than measurements of the absolute type. In this discussion, the effects of spectral quality of light from various light-sources are compared with those produced by the heterogeneous light from tungsten filaments. From theoretical considerations and also from experimental data, it may be concluded that certain advantages of a certain spectral quality of light depend upon the degree to which the light approaches either monochromaticity as one extreme or natural daylight[2] as the other. The tungsten-filament lamp, producing continuous-spectrum light approximating daylight quality in this respect and the sodium-vapor lamp, producing light which is monochromatic or nearly so, represent extremes of spectral quality of light. The effects produced by other illuminants differ mainly in degree rather than in character.

Criteria

The physical, physiological and psychological complexities in seeing are such as to eliminate the possibility of a single criterion which would integrate all phases of seeing and which would permit an adequate interpretation of the experimental results. Therefore, it is necessary to resort to various more or less indirect criteria[3] in each phase. The conclusions drawn from such criteria may be mutually contradictory. For example, it is conceivable that a spectral quality of light, which appears to be ideal when appraised by the criterion of visual acuity, may not be satisfactory for the human seeing-machine operating for long periods under such an illuminant. In this respect, data pertaining to the effects of spectral quality of light are more difficult to interpret into practice than those pertaining to quantity of light. In the latter case, the use of higher levels of illumination represents an approach to daylight intensities of illumination provided by Nature; and in the former case, the use of various spectral qualities of light usually represents departures from the quality of light under which human eyes and human beings evolved.

The criteria presented herewith for the appraisal of the influence of quality of light upon seeing represent only a few of the many which might have been used. As such, they are not to be construed as dictating principles which may be *indiscriminantly* applied to various phases of lighting.

Physical and Physiological Phases

Seeing may be regarded as a chain or cycle of complexities consisting of (1) external factors, (2) eyes and the visual sense and (3) psycho-physiological effects. Objects are visible if the external factors, such as the size, brightness, contrast with background and time of exposure, are above certain limiting or threshold values or combinations. The factors of brightness and contrast are variables which depend upon the spectral quality of the illumination; and of these factors, contrast is generally the more effective in seeing.

Brightness

Sodium-vapor light, being monochromatic or nearly so, eliminates the possibilities of color-contrast. Therefore, a study of the effects of such an illuminant is restricted to the factors of brightness and brightness-contrast which depend upon the spectral quality of the illuminant.

The reflection-factors of 101 specimens of colored paper were measured[4] under equal intensities of illumination from a sodium-vapor lamp and a tungsten-filament lamp, respectively. This number of specimens provides about 5000 pairs, far more than necessary to obtain satisfactory statistical results. The colored papers represented hues throughout the spectrum and included the purples. Several tints and shades of each hue were included as well as a variety of

[2] A. H. Taylor, *The Color of Daylight*, Trans. I. E. S. **25**, 154 (1930); M. Luckiesh, *White Light Versus North Skylight for Color Discrimination*, J. Frank. Inst. **205**, 566 (1928).

[3] M. Luckiesh and Frank K. Moss, *The Human Seeing-Machine*, J. Frank. Inst. **215**, 629 (1933).

[4] M. Luckiesh, *Contrasts in Sodium-Vapor Light*, Electrical World **101**, 827 (1933).

TABLE I. *Average reflectances of 101 samples of red, orange, brown, yellow, green, blue and purple paper under light from a sodium-vapor lamp and from a tungsten-filament lamp.*

	Number of samples	*Average Reflectances* Tungsten (percent)	Sodium (percent)
Higher reflectance under sodium light	42	45.3	52.7
Lower reflectance under sodium light	42	28.5	21.8
Approximately equal reflectance	17	27.2	26.9
All samples	101	35.3	35.5

common shades, such as buffs and browns. The data are condensed in Table I.

It will be noted that the average reflection-factor of all specimens is practically the same under both illuminants. However, for individual specimens the relative brightnesses under equal intensities of illumination vary widely. These data also show that the mean variation in brightness among the samples is greater under the sodium light than under the tungsten light. However, on the basis of the brightness of an object, monochromatic light may or may not be an advantage in the individual case.

Brightness-contrast

For diffusely reflecting surfaces we define brightness-contrast as the ratio of the difference between the two brightnesses divided by the higher brightness. This ratio multiplied by 100 expresses brightness-contrast in percent. No short-cut method could be devised which would reduce to a reasonable limit the time required to ascertain the brightness-contrasts of the entire 5000 possible pairs. Therefore, five specimens were selected from each of six general groups of colors throughout the spectrum and five from the group of purples. The five specimens in each group were so selected that their reflectances formed approximately a geometrical series. They were compared in all possible pairs with results as condensed in Table II.

From a purely numerical standpoint, sodium light enhances brightness-contrast in more cases than tungsten light does. This fact indicates a superiority for sodium light. However, further analysis modifies this advantage somewhat. It

TABLE II. *Average brightness-contrasts of all possible pairs of 35 selected samples of colored papers.*

	Number of pairs	*Average Brightness-Contrast* Tungsten (percent)	Sodium (percent)
Greater under sodium light	267	49.7	65.5
Less under sodium light	152	43.0	28.8
Within 5 percent	176	....	....
	595		

will be noted that the 152 pairs, whose contrasts were greater under tungsten light, had an average contrast lower than the average of the 267 pairs whose contrasts were greater under sodium light. In other words, the tungsten light helped more where visual aid is more generally needed, that is, for generally lower contrasts which are in a lower range of visibility than higher ones. Conversely, it may be said that sodium light enhanced many contrasts that were already high. It may be concluded that sodium light has some advantage in accentuating brightness-contrasts in general, although in many specific cases it completely obliterates brightness-contrast. *It always obliterates color-contrast.* Therefore, it is necessary to weigh the disappearance of color-contrast, far more helpful in seeing than is commonly recognized, against the advantage in brightness-contrast.

Visual acuity

This criterion is a prominent one for appraising the influence of spectral quality of light upon seeing, since it often indicates large and definite differentials between illuminants. In the world of practice, it enjoys an importance, somewhat spurious, due to the fact that it is usually over-emphasized to such an extent that erroneous conclusions are commonly drawn from the experimental data. It is a *threshold* datum, but not necessarily an independent characteristic of visual perception. Measurements of visual acuity indicate that the threshold of visibility is reached by a reduction in the size of the object, while other factors, such as brightness, contrast and time of exposure, remain above their critical or limiting values. By the same interpretation, speed of retinal impression indicates that the threshold condition is reached by reductions in

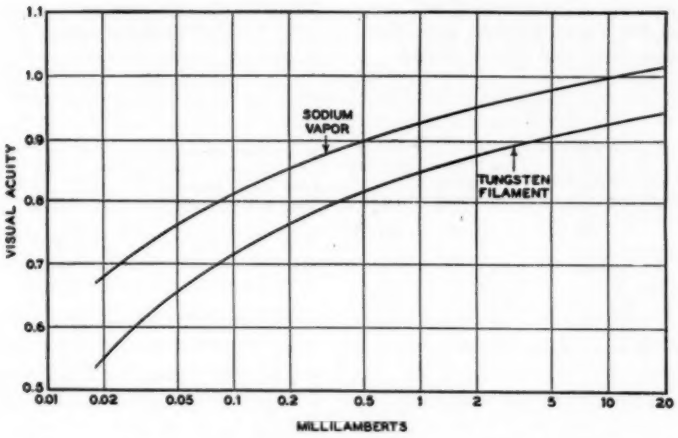

FIG. 1. The relationship between visual acuity and brightness for light from sodium-vapor and tungsten-filament lamps, respectively.

time of exposure while other factors, such as size, brightness and contrast, remain above their critical values. Finally, visual acuity is an important criterion because it can be definitely measured. However, the visual conditions under which it is measured are seldom encountered in everyday seeing. Hence, visual acuity data must be carefully interpreted in order not to give them too much importance, excepting in special cases of very fine work.

Investigations[5] on the dependence of visual acuity upon the wave-length of light indicate that the greatest visual acuity is obtained under monochromatic light from the middle of the spectrum. This fact justifies the emphasis placed in this discussion upon sodium-vapor light as an ideal illuminant for research purposes.

The relationship between visual acuity and brightness for light from a sodium-vapor lamp and a tungsten-filament lamp, respectively, is shown in Fig. 1. Details of the experimental technique are presented elsewhere.[6] It may be concluded from these data that monochromatic light from the sodium-vapor lamp is definitely and significantly superior to the heterogeneous light from the tungsten-filament lamp for revealing detail of small colorless objects. Such a result is to be expected by reason of the elimination or minimization of chromatic aberration in the eye. Subjective reports by the subjects indicate that the details of the test-object appear more distinct under the sodium light than under the tungsten light. These conclusions are based upon measurements involving foveal vision. If the greater visual acuity under sodium light is considered as a practical advantage, it is important to determine whether or not this advantage is sustained over long periods of exacting visual work.

The effect of quality of light on visual acuity has also been determined by the same experimental technique for (1) tungsten-filament light filtered through a concentrated solution of potassium bichromate[7] and (2) for light from the mercury-arc lamp.[8] For brightness-levels of the order of one-tenth of a millilambert, the relative effectiveness per unit brightness of these light-sources may be estimated as follows:

[5] M. Luckiesh, *The Influence of Spectral Character of Light on the Effectiveness of Illumination*, Trans. I. E. S. **7**, 135 (1912); M. Luckiesh, *The Dependence of Visual Acuity on the Wave-length of Light*, Electrical World **58**, 1255 (1911); M. Luckiesh, *Color and Its Applications*, D. Van Nostrand Co., New York, 1915, 1921.

[6] M. Luckiesh and Frank K. Moss, *Visual Acuity and Sodium-Vapor Light*, J. Frank. Inst. **215**, 401 (1933).

[7] M. Luckiesh and Frank K. Moss, *The Effect on Visual Acuity of Shortening the Spectrum at the Blue End*, J. O. S. A. **10**, 275 (1925).

[8] M. Luckiesh and Frank K. Moss, *Visual Acuity Under the Mercury Arc and Tungsten-Filament Lamp*, J. Frank. Inst. **205**, 565 (1928).

1, Unfiltered light from tungsten-filament lamp
1, Unfiltered light from mercury-arc lamp
2, Filtered light ($K_2Cr_2O_7$) from tungsten-filament lamp
4, Monochromatic light from sodium-vapor lamp

This method of comparing various light-sources has little significance for the higher brightness-levels, as is obvious from Fig. 1.

These data indicate that visual acuity increases as the spectral quality of the light approaches monochromaticity. In the case of the mercury-arc lamp, apparently the violet and blue hues, contributing only a few percent of the total light, seem to overcome the relative monochromatism of the green and yellow lines. Little or no advantage in visual acuity can be expected by combining vapor lamps with tungsten-filament lamps in a single lighting unit.

The advantage of light of a restricted spectral quality, as appraised by visual acuity, is apparently significant only for the relatively few visual tasks involving objects of threshold or near-threshold size. Fine engraving may be cited as an example. Normal eyes are able to resolve objects separated by a distance subtending approximately 1 minute visual angle. This is equivalent to a linear distance of 0.004 inch when viewed from a distance of 14 inches. At a distance of 200 feet, a visual angle of 1 minute corresponds to a separation of about 0.7 inch. Obviously, a discrimination of detail of such an order is not a usual requirement of everyday seeing. The disadvantages of unnatural color environment obviously offset the advantage of greater definition of small details to some extent. In general, it may be concluded that any *net* advantage in visual acuity due to an approximation of monochromatism is an economic one, since the same effect could be obtained with higher intensities of heterogeneous light.

Speed of retinal impression

If threshold conditions are obtained by shortening the time of exposure, it is possible to obtain visibility measurements pertaining to objects of various sizes. Hence, the influence of chromatic aberration may be practically eliminated. Usually, it is necessary to decrease the contrast of the test-object with its background as the size is increased in order to reach the visual threshold at brightness-levels comparable to those encountered in practice.

TABLE III. *Threshold time required to recognise a large object of low contrast and a small object of high contrast under sodium-vapor and tungsten-filament light.*

	Time in Thousandths of a Second			
Subject	Brightness, size, contrast, Tungsten	0.1 ml 10 minutes 11 percent Sodium	Brightness, size, contrast, Tungsten	1.0 ml 1.17 min. 100 percent Sodium
1	208	223	220	131
2	...	...	403	292
3	250	257	333	278
4	275	267	220	183
5	347	339	270	208
6	236	217	269	172
7	...	...	348	316
8	199	207	294	171
9	310	292	...	...
10	178	170	267	182
Geometric mean	245	242	286	207

The data presented in Table III indicate the speed of retinal impression for a small object of high contrast and a large object of low contrast, respectively, under sodium light and tungsten light. The research technique was similar to that used in researches which have been described in detail elsewhere.[9]

It will be noted from these data that the sodium light is distinctly superior to tungsten light in the case of small objects of high contrast when appraised upon a basis of speed of retinal impression. This result is to be expected, since the image of the test-object is more sharply defined upon the retina under the sodium light than it is under the tungsten light. This differential in speed of retinal impression is considered to result from the minimization of chromatic aberration rather than from any inherent difference in time of photosensory reactions under the two illuminants.

In the case of the larger object, no differential in speed of retinal impression was observed under the two illuminants. This result is predicted by theoretical considerations. Speed of retinal im-

[9] P. W. Cobb and Frank K. Moss, *The Relation Between Extent and Contrast in the Liminal Stimulus for Vision*, J. Exp. Psych. 10, 350 (1927).

pression is a criterion of obvious importance in determining the relative value of illuminants in highway lighting. It is of considerably less importance for the usual tasks of the work-world.

A similar research compared tungsten light with filtered light of approximate daylight quality. No significant difference in speed of retinal impression was observed. In general, it may be concluded that speed of retinal impression, when extraneous factors are eliminated, is not a function of the spectral quality of the stimulus to any significant extent in everyday seeing.

Pupillary area

Since the receptors for the pupillary light reflex are assumed to be identical with those pertaining to vision, a study of the relationship between pupillary area and the spectral quality of the stimulus is of theoretical interest at least. The pupillary measurements[10] presented in Table IV were made after an adaptation period of

TABLE IV. *Each value of pupillary diameter presented in the table represents the average of 5 series of 5 measurements each.*

	Diameter of Pupil, Millimeters			
	0.1 ml		1 ml	
Subject	Tungsten	Sodium	Tungsten	Sodium
1	5.80	5.96	5.29	5.54
2	6.90	7.13	6.44	6.74
3	4.67	5.00	4.02	4.21
4	6.53	6.78	6.12	6.59
5	5.48	5.78	4.73	4.98
6	5.37	5.65	4.66	4.69
7	7.24	7.53	6.84	7.13
8	6.67	6.94	6.16	6.36
Average	6.08	6.35	5.53	5.78

15 minutes to brightness-levels of 0.1 and 1 millilambert, respectively. The illuminated field to which the eyes were adapted was 9 by 10° in extent and its surroundings were comparatively dark. These data indicate that the average pupils of eight subjects were 9.0 percent and 9.4 percent larger in area under the sodium-vapor light than under the tungsten-filament light for brightness-levels of 0.1 and 1 millilambert, respectively. These differences are considered significant when compared with their respective probable errors.

Although the pupils are somewhat larger under sodium-vapor light than under tungsten-filament light, the advantage in seeing derived from this factor, due to increased brightness of the retinal image, is not great. Hence, the general assumption may be made that differentials, if any, in pupil size due to the spectral quality of light are not important in seeing on a basis of quantity of light admitted to the retina.

Nervous muscular tension

It is a matter of everyday experience that nervous tension and fatigue commonly cause a tightening of certain muscles. For example, a pencil may be held more tightly when one is nervous or after the muscles of the hand or arm have become fatigued from a long period of writing. In the latter case, the effect of the fatigued muscles is indicated by the reaction of these muscles. It may also be observed that muscular energy is often wasted as a result of strain or fatigue which originates remotely from the place where it may manifest itself. An automobile driver commonly grips the steering-wheel more tightly at night on a poorly lighted street than on a well-lighted one. In this case, an inadequacy in conditions for seeing is manifested in the useless expenditure of energy. The method evolved to appraise nervous tension consisted in measuring the changes in muscular tension as registered by the fingers of the left hand while the subject was engaged in the task of reading. The research technique is described in detail elsewhere[11] in connection with an extensive investigation which showed that nervous muscular tension resulting from reading decreased as the intensity of illumination was increased. In fact, this work provided the first scientific indication that daylight intensities are ideal for continuous visual work.

The results of an investigation involving four subjects indicated the same degree of nervous muscular tension while reading under sodium light and tungsten light, respectively. The reading was performed for periods of thirty minutes

[10] Frank K. Moss, *A Modified Broca Pupillometer*, J. O. S. A. 22, 735 (1932).

[11] M. Luckiesh and Frank K. Moss, *A Correlation Between Illumination Intensity and Nervous Muscular Tension Resulting from Visual Effort*, J. Exp. Psych. 16, 540 (1933).

and under an intensity of illumination of fifteen footcandles. In response to questions, the subjects reported that the ease and comfort in reading under the two illuminants seemed to be about the same.

Asthenopia

There is some evidence, largely of a subjective character, which indicates, in certain anomalous cases of vision, that the eyes tire more quickly while reading under light from tungsten filaments than under the same intensities of natural daylight illumination. This evidence is in harmony with the philosophy that the ideal quality (or quantity) of light is that quality (or quantity) under which the eyes evolved. It is conceivable that some advantage in minimizing "eye-fatigue" might be secured by a reduction of the infrared radiation reaching the eyes.[12] However, the lack of comprehensive criteria for appraising eye-fatigue is a serious handicap in investigating this possibility.

Psychological Phases

Illusions

It is not infrequently that the attempt is made to explain certain visual effects upon a basis of physiological optics when, actually, the phenomena arise from psychological causes. For example, it is commonly believed that an object viewed against a small brightly illuminated field situated amid dark surroundings can be seen more quickly and distinctly than is the case when the entire visual field is illuminated to the same intensity as the immediate background of the object. Measurements of speed of retinal impression and visual acuity indicate that the reverse is true. In the subjective appraisal of these two conditions for seeing, the psychological factor of *concentration of attention* submerges the actual effects upon the visual functions.

It is also well known that small objects seem to be more sharply defined when viewed under mercury-arc light than under tungsten-filament light of equal intensities of illumination. Actual measurements of visual acuity indicate that there is no significant difference between these illuminants in this respect. Since the apparent greater definition under mercury-arc light does not reveal itself in measurements of visual acuity, the effect must be an illusion. In fact, there are so many illusions[13] involved in seeing that one must be on the lookout for them in analyzing any condition of seeing.

For several years a blue-bulb tungsten-filament lamp was advocated by some for use in automobile headlamps, although the facts of physics favor a yellowish light as compared with a whiter light for headlamps. This paradox is readily explained on the basis of an illusion. Owing to such factors as dimmers, poor contacts and depleted batteries, the voltage of lamps is often reduced and, consequently, the yellowishness of the light is increased and the quantity of light decreased. Through many such experiences yellowishness becomes associated with less light and poor seeing. Conversely, the whiter light from the blue bulbs becomes associated with more light and better seeing. Thus an illusion initially exists, which, as in the case of most illusions, will eventually be overcome by accumulated or mass experience, if the latter eventually reveals no advantage. The popularity of the blue-bulb headlamp was explained on the basis of this illusion and its eventual disappearance from use was successfully predicted.[14]

Highways illuminated by sodium-vapor lamps may appear to be "better lighted" than when illuminated by tungsten-filament lamps producing the same intensity of illumination on the roadway. It is entirely possible that this effect is an illusion. The explanation may be that grass, foliage and many other features of the surroundings are actually darker under the sodium light and hence, the roadway appears brighter by reason of contrast with the surroundings. Glare from automobile headlamps may seem to be greater on a highway illuminated by sodium lamps. This may be real or an illusion. These and other factors must be studied before predictions can safely be made; but at least it can safely be emphasized that illusions are ever-present in seeing.

[12] M. Luckiesh, *Infrared Radiant Energy and the Eye*, Am. J. Physiol. **50**, 383 (1919).

[13] M. Luckiesh, *Visual Illusions*, D. Van Nostrand Co., New York, 1922.

[14] M. Luckiesh, L. L. Holladay and A. H. Taylor, *Relative Glare of Moderately Colored Lights*, J. O. S. A. and R. S. I. **11**, 311 (1925).

Summary

For simplicity, the principal conclusions are presented for sodium-vapor light compared with tungsten-filament light on the basis of equal intensities of illumination.

The advantages, if any, of a specific spectral quality of light correspond with the degree to which the light approaches either monochromaticity as one extreme or natural daylight as the other, depending upon the character of these advantages.

The average reflectance of 101 colored papers representing tints, shades and fairly pure colors throughout the spectrum (and including purples) is about the same under both illuminants. The difference in reflectance of individual media varies widely and may be in favor of either illuminant.

The brightness-contrast of various pairs of colored papers is higher in more cases under sodium light than under tungsten light. However, this apparent advantage is modified by the fact that the average brightness-contrast under sodium light was rather high for the 267 pairs whose contrasts were greater under sodium light than under tungsten light. Also, the average brightness-contrast under sodium light was rather low for the 152 pairs whose contrasts were lower under sodium light.

Color-contrast disappears entirely under sodium light. It is more important in everyday seeing than is commonly believed. This general disadvantage must be weighed against any advantage in brightness-contrast. The complete distortion of color and the absence of color-contrast naturally limits initial consideration of sodium light to low-intensity lighting, such as country highways, and to special cases of inspection and critical seeing of fine details.

Visual acuity is definitely and appreciably greater under sodium light than under continuous-spectrum light. This is due to the minimization of chromatic aberration. In fact, mercury-vapor light shows no advantage in this respect over tungsten-filament light. Doubtless this is due to the presence of relatively powerful blue and violet lines in mercury-vapor light. These render this light practically as unmonochromatic from the viewpoint of visual acuity and chromatic aberration as a continuous-spectrum light. It is emphasized that visual acuity is not a comprehensive criterion for appraising the influence of spectral quality in every-day visual tasks. In fact, it is much over-rated in practical importance.

Speed of retinal impression, when extraneous factors are eliminated, apparently is not a function of the spectral quality of light in everyday seeing. It is an important factor in many visual tasks and particularly on the highway. Small objects of the order of one-minute visual angle can be seen more quickly under sodium light than under tungsten-filament light. Obviously, visual acuity is a dominating factor in such cases. There is no appreciable difference between these two illuminants in regard to the time required for recognition of large objects.

The pupils of the eyes are somewhat larger under sodium light than under tungsten light. However, the difference is not important on the basis of seeing because of higher brightness of the retinal image.

Nervous muscular tension resulting from reading was about the same for the two illuminants.

Illusions are ever-present in seeing and some apparent advantages in seeing have been explained by them. They should be taken into account in connection with certain observations under sodium-vapor lighting.

The Purkinje effect should militate against sodium light at very low intensities of illumination, for it is well known that there is a decided shift of the maximum of the spectral visibility curve of radiation toward shorter wave-lengths. However, this is chiefly of interest academically or, at best, in very special cases. The state of adaptation of the retina is determined by the high brightnesses in the visual field. In artificial lighting, on the highway and elsewhere, relatively high brightnesses, far above the Purkinje range, are generally present. Adaptation entirely to very low brightnesses is necessary to experience this phenomenon. Besides, it is practically absent in strictly foveal vision.

Experience so far indicates that the yellowishness of sodium light is not particularly annoying or objectionable when performing *critical* visual tasks which do not involve color discrimination. However, the psychological effect of color-

distortion and absence of color-contrast in the surroundings is what one may expect from such unnaturalness. Many years of experience of a similar nature with mercury-vapor light are available. Certainly the consensus is scarcely a favorable one when familiar objects and environment appear grossly unnatural.

Glare due to sodium-vapor light or to other sources in an environment of sodium-vapor lighting has not been studied quantitatively but from other experiments on colored light no great difference is to be expected.

Seeing is a prolonged activity in everyday visual work. Therefore, a complete appraisal must eventually include the effect upon human seeing-machines of long periods of work under sodium light. This has not been determined.

In the present state of knowledge one may conclude, tentatively at least, that such advantages of sodium-vapor light as may result from higher luminous efficiency or greater visual effectiveness are chiefly economic in character. Excepting in very special cases, the same visual assistance may be secured by the use of higher intensities of illumination with heterogeneous light.

Microscopic Study of Pigments Using Ultraviolet Light*

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(Received November 20, 1933)

The idea of using the ultraviolet microscope in order to study the component parts of two pigment systems was suggested by Green some years ago. The development of the technique to the necessary degree of refinement has been slow but seems now to have reached a point where valuable information is obtainable. This article shows photomicrographs of lithopone, titanium-barium, titanium-calcium pigments in which the ZnS or TiO_2 is pictured as opaque particles and the barium or calcium sulfate as transparent particles. This permits the investigator to study the relative size of each component as well as the amount of coalescence.

IN a previous article[1] the authors describe the advantage to be gained by using ultraviolet photomicrography in the determination of the average size of pigment particles which approach the limit of resolution of the ordinary microscope. The additional resolution attained has added materially to the accuracy of the photomicrographic method of particle size determination.

In the present article a further application of this technique to the study of pigment has been made. This application is involved in the study of pigment systems in which the various components have different ultraviolet absorption characteristics, such as mixtures of titanium dioxide or zinc sulfide with calcium or barium sulfate, or co-precipitated pigments such as lithopone or titanium barium pigment.

In order to avoid confusion, this article will deal specifically with lithopone but it should be borne in mind that the study and finding apply equally to the calcium sulfate and barium sulfate-titanium pigments.

Lithopone is the precipitate formed when barium sulfide liquor is added to zinc sulfate solution and is composed of approximately molecular proportions of zinc sulfide and barium sulfate. It is necessary, subsequent to precipitation, to calcine the material at fairly high temperatures in order to dehydrate the zinc sulfide and to increase the particle size of the colloidal crude lithopone to that of a pigment of optimum optical properties.

Many theories have been advanced regarding the form in which zinc sulfide and barium sulfate exist in lithopone. These conceptions, based on either the precipitation or calcination, or both, range from a product in which one component is dissolved in the other to one in which the zinc sulfide and barium sulfate exist as distinct crystals. Among the ideas that have received attention is that of a compound crystal of lithopone, part of which is zinc sulfide and the balance of the crystal barium sulfate. Another proposal is that of rhythmic precipitation, in which the crystal is built up by alternate layers of zinc sulfide and barium sulfate being deposited on a precipitation nucleus. The possibility of a solid solution of zinc sulfide in barium sulfate has not been seriously considered owing to x-ray evidence which indicates the presence of barium sulfate in its true crystal form.

The theory that has received the most support is that the barium sulfate has a coating of zinc sulfide which renders the zinc sulfide highly efficient by creating a great deal more surface of the highly refractive material. It has been suggested that this condition has been brought about in the calcining process, due to the zinc sulfide distilling over and recondensing on the barium sulfate particles.

Green suggested some years ago that definite information on this subject should be obtainable through the medium of the ultraviolet microscope. Since zinc sulfide is so very opaque to

* Presented at the meeting of the Optical Society of America, February 24–25, 1933.

[1] Haslam and Hall, J. Frank. Inst. 209, 777 (1930).

ultraviolet light and barium sulfate relatively transparent, a photomicrograph taken by this means should show very definitely the existence of any free barium sulfate. This idea was put in practice and the results obtained showed that there are particles of free barium sulfate present. However, on measuring the particle size of this material from photomicrographs and calculating the weight of the two components he found only about twenty-five percent by weight of barium sulfate, whereas by chemical analysis of the product it was known to contain seventy percent by weight of barium sulfate. These measurements led to the conclusion that the remainder of the barium sulfate particles must have a coating of zinc sulfide which rendered them opaque to ultraviolet light and were, therefore, measured as zinc sulfide particles.

This work was the first concrete evidence concerning the nature of lithopone and the present study involves the development of the technique used in order to establish more conclusively the structure of the pigment. The photomicrographs involved in the original work were not particularly good, due primarily to the use of a mounting medium not well suited for the investigation. In continuing this pioneer work, a thorough study has been made of numerous mounting media that might be suitable for the study at hand. Obviously, there are several requisites for such a material. It should act as a dispersing agent for the pigment, it should have an ultraviolet transparency quite different from either zinc sulfide or barium sulfate and it should have an index of refraction reasonably different from either of the components of lithopone. This latter requisite was found to be relatively unimportant, since the differences in transparency were found to be relatively great.

Besides these specific properties desirable for the study of lithopone, it was also necessary that the material chosen have all the properties of a good microscopic mounting medium. In other words, it must lend itself to the preparation of a mount satisfactory for microscopic observation and photography. Such a mount must be prepared so that:

(1) All states of aggregation are eliminated, if one is interested in the ultimate particle.

(2) The ultimate particle must not be broken or ground during the process of dispersion.

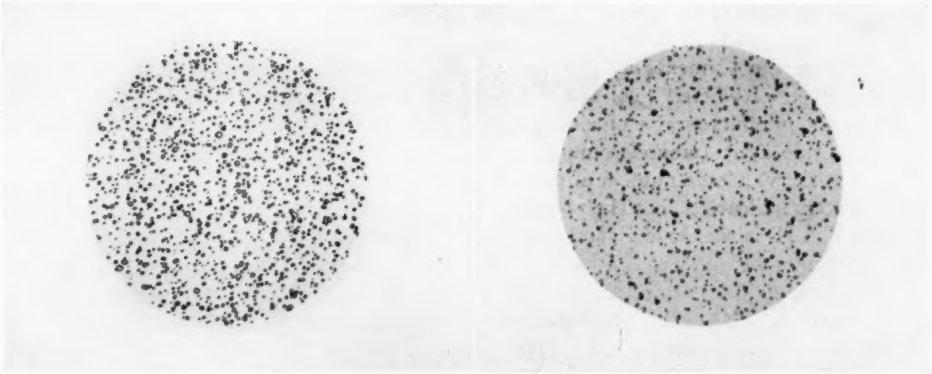
(3) The various components of the material being examined must be present in their true proportions.

(4) There must be enough particles present to give a correct average.

(5) The particles must all be in one plane.

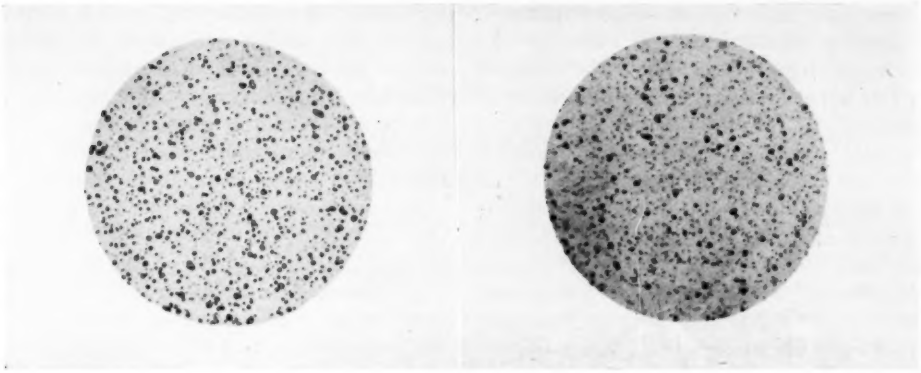
A study was made of a large number of resins and gums, both natural and synthetic, as well as a number of other materials, and Cumar gum was finally selected for the investigation as being the substance approaching most closely to the ideal.

Cumar gum (paracoumarone resin) $(C_6H_4CH\ O\ CH)_M$, is a synthetic resin produced from coal tar distillates. It contains *p*-coumarone, *p*-indene,



A B

FIG. 1. Photomicrographs of zinc sulfide. (A) Using visible light. (B) Using ultraviolet light.



A B

FIG. 2. Photomicrographs of titanium dioxide. (A) Using visible light. (B) Using ultraviolet light.

and polymers of other hydrocarbons. It is insoluble in alcohol but soluble in mineral spirits. It differs from natural resins in being optically inactive and in having a lower melting point.

This material has an index of refraction fairly close to that of barium sulfate but fortunately has an ultraviolet transparency between barium sulfate and zinc sulfide. This fortuitous circumstance permits the photography of lithopone in such a way that the zinc sulfide crystals and barium sulfate crystals are quite clearly defined. The photomicrographs obtained in this manner depict the zinc sulfide as very opaque (black) particles and the barium sulfate as clear transparent (white) particles while the background of cumar gum is of intermediate intensity (gray).

It is not the purpose of this paper to describe the technique involved in the mounting or photographing of the pigments as the method has been described elsewhere.[1]

Fig. 1A is a photomicrograph of zinc sulfide taken with visible light (monochromatic light $\alpha = 4480$A) and shows a large number of particles with clear centers indicating that the pigment is transparent. Fig. 1B is the same pigment photographed with ultraviolet light, the mounting medium being cumar gum. Since zinc sulfide is opaque to ultraviolet light, the clear centers are no longer visible, the individual particle appearing as black particles on a gray background. Figs. 2A and 2B show titanium dioxide, A in blue light and B in ultraviolet light.

Figs. 3A and 3C are photomicrographs of $BaSO_4$ showing two extremes of particle size. Owing to the low index of refraction, the photography is not particularly satisfactory. These photomicrographs required a mounting medium (para-meta ester gum) quite different from cumar or dammar gum and a considerable longer exposure in order to get the best results with visible light. Figs. 3B and 3D show the same pigments photographed with ultraviolet light using cumar gum for mounting.

In the case of lithopone, if the picture is taken with visible light with a mounting medium most satisfactory to show the zinc sulfide, it is apparent that the barium sulfate is not visible at all. Photomicrographs of lithopone, calcium-titanium pigment and barium-titanium pigment taken with visible light are shown in Figs. 4A, B and C.

The same three products photographed with ultraviolet light are shown in Figs. 5A, B and C. Here, then, is a method of recording the true relation of the components of pigments of this nature in which the black opaque particles of zinc sulfide, the clear transparent particles of barium sulfate and the gray background formed by cumar gum may be clearly differentiated.

The value of this picturization cannot be overestimated. From photomicrographs such as this, the size and shape of the individual particles, as well as the quantity of each of the two components, can be determined. It is also possible to determine the amount of pigment that

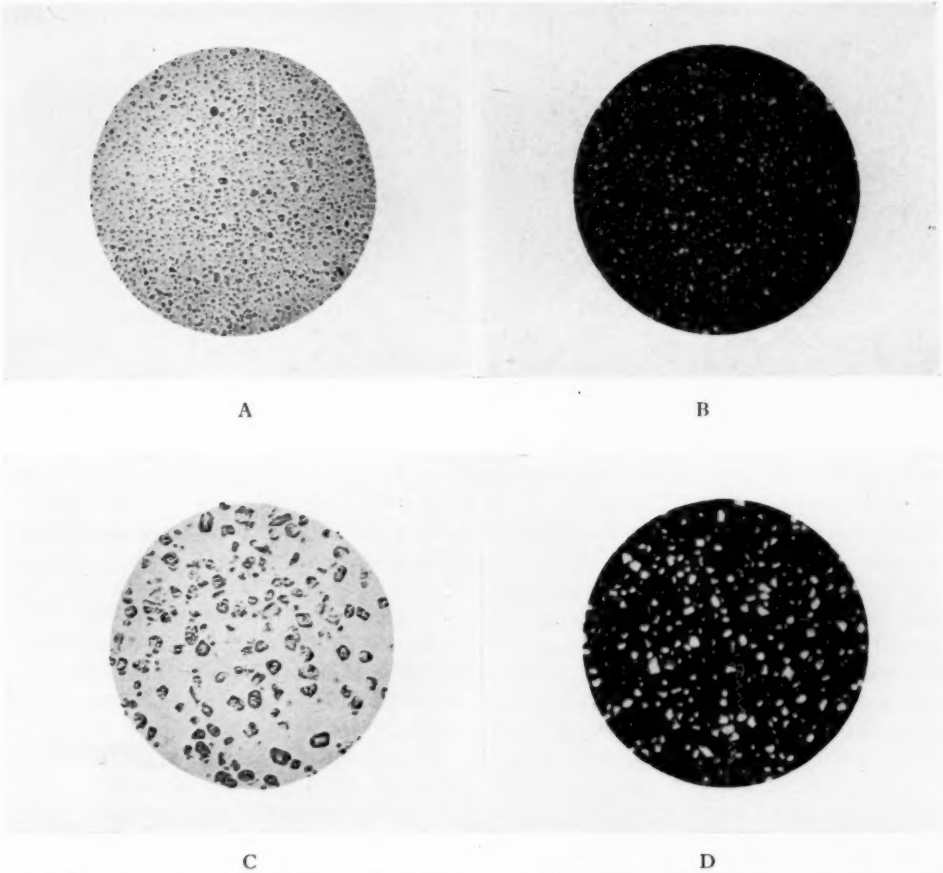


FIG. 3. Photomicrographs of barium sulfate. (A) Fine pigment—visible. (B) Fine pigment—ultraviolet. (C) Coarse pigment—visible light. (D) Coarse pigment—ultraviolet light.

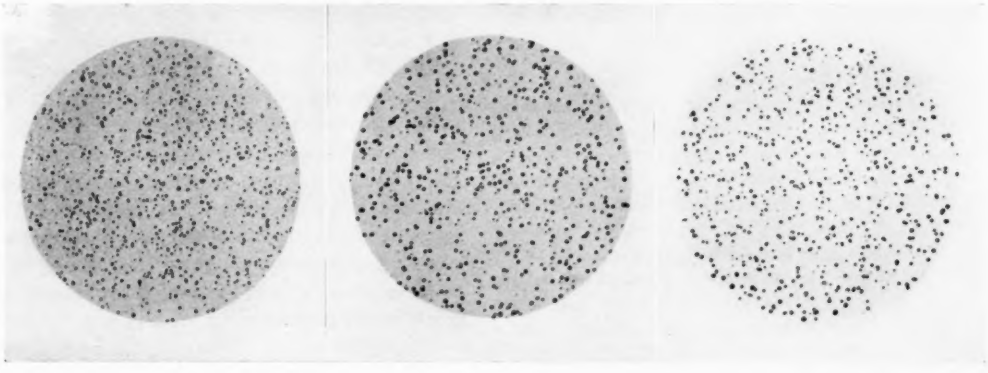
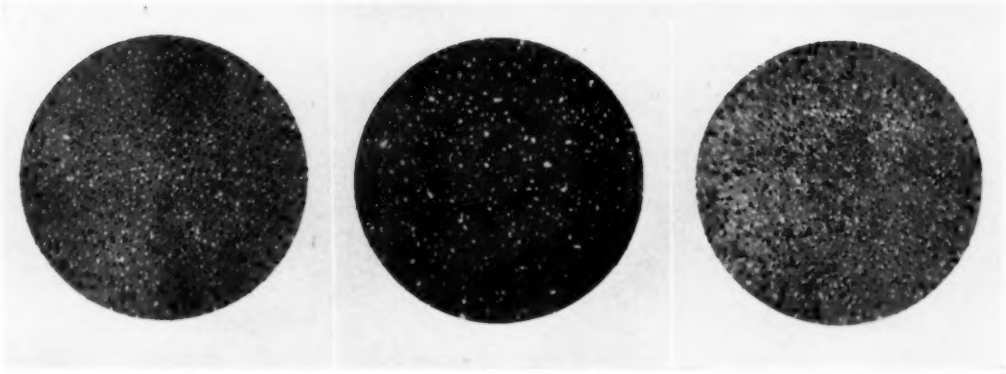


FIG. 4. Photomicrographs with visible light. (A) Lithopone. (B) Calcium-titanium pigment. (C) Barium-titanium pigment.



A B C

FIG. 5. Photomicrographs with ultraviolet light. (A) Lithopone. (B) Calcium-titanium pigment. (C) Barium-titanium pigment.

is present as combined particles; that is, zinc sulfide adhering to barium sulfate. With the development of this technique it is obvious that a means has been devised to study with real satisfaction the individual components of a two-pigment system in which the ultraviolet absorption of the pigment is different. A new stage in the development of co-precipitated pigments has been reached and the understanding of differences occurring in these pigments, hitherto obscure, which are dependent on relative sizes of zinc sulfide and barium sulfate is now within the reach of the microscopist who is willing to apply ultraviolet photomicrography.

CONCLUSIONS

A method for studying the individual components of co-precipitated pigments has been developed with the aid of the ultraviolet microscope.

It has been established that the co-precipitated pigment contains individual particles of each of the two components and is not a completely coalesced product as has been intimated.

A Reflection Densitometer

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(Received November 10, 1933)

A reflection densitometer designed primarily for research and product control on photographic printing papers is described in detail. It can be used also in connection with photo-mechanical half-tone reproduction work. Simplicity of design and relatively low cost of construction is combined with precision ample for all practical purposes. The paper concludes with a short description of factors influencing the measurement of reflection density.

THIS is an optical instrument for visually measuring the reflecting power of small surface areas by photometric match and has a special application in the sensitometry of photographic paper. It was designed and built in answer to a demand for an inexpensive device of high precision for both research and product control on photographic paper. It is also useful in half-tone work and other branches of photo-mechanical printing. It is essentially a modification of the Capstaff-Purdy densitometer, which was first marketed by the Eastman Kodak Company in 1929 and which has proved entirely satisfactory.

The Fundamentals of Reflection Densitometers

The fundamental requirements of an instrument for this purpose are precision, repeatability of results, simplicity, compactness and low cost. The elements of such an instrument are two optical systems, one of which illuminates the sample to be measured and collects light diffusely reflected from it. The other system provides a field for a brightness comparison with the first. Light from the two systems is made to form the two parts of a photometric field. These two parts may be matched for brightness by a suitable light-modulating device placed in either system. The required setting of the modulating device gives the reflecting power of the sample. Both optical systems usually have as their light source one and the same lamp.

The constructional factor of greatest importance is the method by which the light intensity is modulated. This modulation may have as a basis any of the following: (1) The inverse square law; (2) variable diaphragms; (3) polarization; (4) calibrated absorbing wedges; (5) the cosine law.

Instruments of the first three types can be primary, that is, the modulating device may be calibrated directly from the theory involved. Secondary instruments require calibration using some primary type of modulation. All absorbing wedge instruments are therefore of the secondary type. Instruments of the first four types have been described, as given in the appended bibliography. Among them may be mentioned the inverse square law instruments described by Benson, Ferguson and Renwick[1] and by Kendall;[2] diaphragm instruments by Jones, Nutting and Mees,[3] by Davies,[4] and by Cartwright and Hallam;[5] absorbing wedge instruments by Gold-

* Communication No. 516 from the Eastman Kodak Research Laboratories, Rochester, New York.

[1] D. E. Benson, W. B. Ferguson and F. F. Renwick, *A Convenient Accurate Photometer for the Measurement of Photographic Densities*, Phot. J. **58**, 155–166 (1918).

[2] C. W. Kendall, *Reflection Densitometer for Photographic Papers*, Rev. Sci. Inst. **3**, 668–74 (1932).

[3] L. A. Jones, P. G. Nutting and C. E. K. Mees, *The Sensitometry of Photographic Papers*, Phot. J. **54**, 342–59 (1914). See also P. G. Nutting and L. A. Jones, *A Transmission and Reflection Densitometer for Small Areas*, Trans. Illum. Eng. Soc. **9**, 611–13 (1914).

[4] E. R. Davies, *Electrical Measurement of Reflection Density*, Part I, Phot. J. **72**, 57–73 (1932); Part II. *New Photo-Electric Reflection Density Meter*, Phot. J. **72**, 118–27 (1932).

[5] H. M. Cartwright and C. D. Hallam, *A New Reflection Densitometer*, J. Sci. Inst. **3**, 246–8 (1926).

berg,[6] Winther and Mynster,[7] Filmograph[8] and by Geoghegan (the Tallent instrument).[9] So far as the writer is aware, no instrument using cosine law modulation has been proposed.

In designing the present instrument, all these methods of modulation were considered. The possibilities of physical methods, that is, of using the response of a photosensitive device instead of a visual photometric match, were also considered. It was concluded that the requirements enumerated above could be well met by an instrument using a calibrated absorbing wedge. One factor affecting this conclusion was the experience this laboratory has had with the transmission densitometer of this type.[10] The absorbing wedge used in the present instrument is similar to that used in the transmission densitometer. It is a photographic plate suitably exposed and developed. These wedges are practically nonselective and very stable under the intensity used.

Description of the Instrument

The essential parts are shown diagrammatically in Fig. 1. The sample S, which is held against the mask M by the clamp C, is illuminated at 45° to the normal and is viewed along the normal. Lamp A illuminates S through the diaphragm B, which reduces the beam to cover just more than the region measured, thus eliminating stray light. The light diffusely reflected along the normal from the sample is made to form one part of the photometric field in the following way: G is a silvered mirror facing upwards, from the center of which a small circular patch of silver is removed. Light from the sample passes up through this clear central area and appears

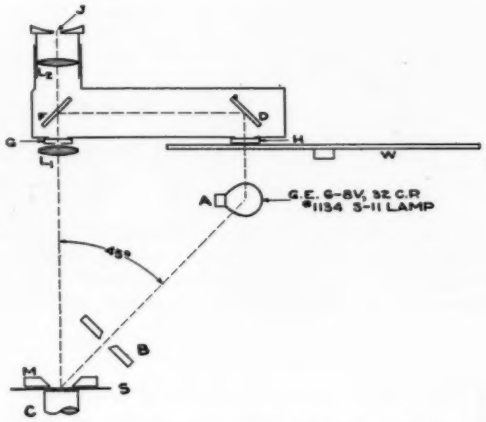


Fig. 1. Diagram of optical system of reflection densitometer.

as the test part of the photometric field. Immediately below this mirror is the lens L_1, which, in combination with L_2, creates an image of the sample surface just above the stop J. This image falls in the lens of the observer's eye. All the light forming this image passes, of course, through the clear central area of the mirror. In this way the surface texture of the sample is not seen at all, the light from the sample is effectively integrated and the clear central part of the mirror appears to be of a perfectly uniform brightness. This brightness is proportional to the reflecting power of the sample.

The reflecting surface of the remaining annular portion of the mirror appears as the comparison field and is illuminated in the following way: Light from the same lamp A passes through the photographic wedge W, through the flashed opal plate H, is reflected at the mirror D, partially reflected downwards by the glass plate F and strikes the photometric mirror G. From the reflecting outer portion of the mirror it is reflected back, is transmitted by the glass plate F and brought into the stop J by the lens L_2. The reflecting annular portion of the mirror, therefore, appears as the comparison field. The comparison field can be adjusted for brightness by rotating the circular photographic wedge W and a photometric match obtained. The field is seen with the unaccommodated eye by the action of lens L_2. This method of obtaining the photometric field is that of Capstaff[10] and is

[6] E. Goldberg, *Densograph*, Kinotechnik **5**, 529–31 (1923). W. Seifert, *New Model Goldberg Densograph*, Phot. Ind. **28**, 1364–66 (1930).

[7] C. Winther and E. H. Mynster, *A Paper Densitometer*, Zeits. f. wiss. Phot. **24**, 298–304 (1926).

[8] *The Filmograph Densitometer*, Photographe **15**, 62 (1928).

[9] G. Geoghegan, *Tallent Reflection Density Comparator*, Phot. J. **71**, 360 (1931). S. Read, *New Instrument of A. A. Tallent for Measurement of Reflection Densities*, Ber. VIIIth Intern. Congress of Photography, Dresden, p. 142, 1931.

[10] J. G. Capstaff and R. A. Purdy, *A Compact Motion Picture Densitometer*, Trans. Soc. Mot. Pict. Eng. **11**, 607–12 (1927).

used in the transmission densitometer mentioned above. It was originally used on an inverse square law densitometer,[11] which instrument also appears to be the first to move the lamp between two diffusing screens, so that a great range of modulation was accomplished with a small lamp movement.

Returning to the system which images the sample surface, we find that this image is near the stop J; then the actual area of the sample used for measurement is fixed by the magnification and by the size of the stop J. The area on the sample thus fixed is a circle of about 4 mm in diameter. As stated above, the light diffusely reflected from this area is integrated to afford a uniform field for photometric matching. The advantage of this arrangement is that rough-surfaced papers and half-tone mechanical prints offer no difficulties, even to the unskilled observer.

An adjustment, which is not shown, is provided to move lamp A toward H to allow for zero setting, so that the scale may read zero for a fixed-out paper stock of a particular reflecting power. Fixed-out photographic papers differ slightly in their reflecting powers from 65 to 85 percent as compared with magnesium carbonate. Therefore, the adjustment necessary is slight and is not enough to disturb the 45° angle of illumination to an appreciable degree. The lamp A used in this instrument is a General Electric, 6–8 volt, double contact, Mazda No. 1134, smooth bulb, S-11. It is operated from a transformer incorporated in the instrument, which requires a 60 cycle 110–120 volts a.c. supply.

The photographic wedge used is similar to that used in the transmission densitometer referred to. It is, however, calibrated differently and its direction of increasing density is opposite. Therefore, the wedges for the two types of instruments are not interchangeable.

The experimental model of this instrument is shown in Fig. 2. A sensitometric strip is held in place for measurement. The scale appears at the index window to the right of the eyepiece. The plunger on the lower surface operates the sample clamp. It is possible to measure an area at the center of quite large prints.

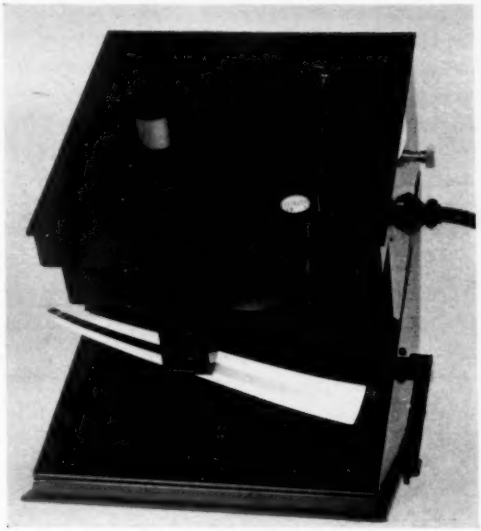


FIG. 2A. Instrument arranged to read from sensitometric strips and prints.

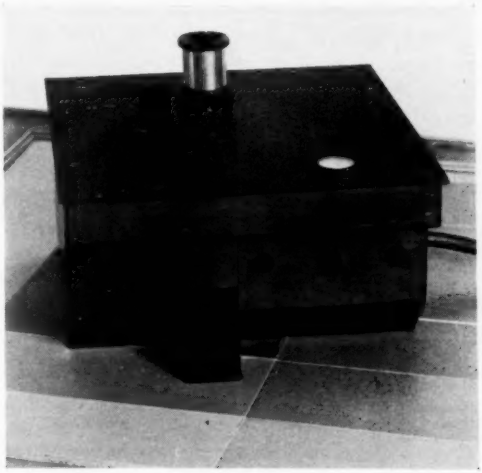


FIG. 2B. Instrument split, to read from large areas.

The scale of the instrument does not read in reflecting power but in reflection density units. Reflection density is defined as the logarithm of the reciprocal of the reflecting power, or $D_R = \log (1/R)$.

[11] J. G. Capstaff and N. B. Green, *A Motion Picture Densitometer*, Trans. Soc. Mot. Pict. Eng., No. 17, 154–9 (1923).

This instrument has been checked against the standard reflection densitometer here in the laboratory and the agreement is very satisfactory for all density values and all surfaces.

Data to Illustrate Performance

To illustrate the repeatability of results, Table I is included. The figures are single readings of reflection density values for one sensitometric strip of a glossy chloride paper. The different columns represent readings made by different observers on different days. The readings were made rapidly, as is customary in routine work.

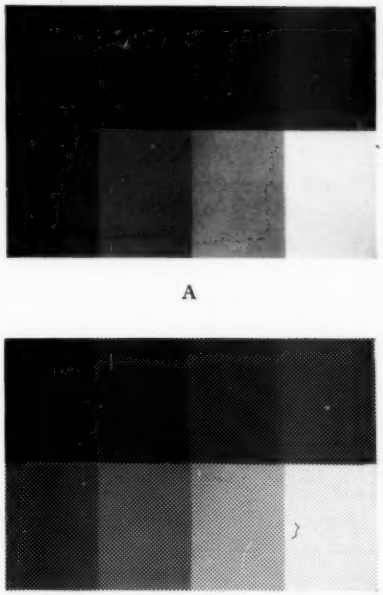
To show the application of the instrument to tone reproduction in photomechanical printing, the data in Table II are given. These figures are reflection density readings made on a test object consisting of a series of neutral gray surfaces.

Table I. *Reflection density readings on one sensitometric strip of glossy chloride paper.*

Step No.	*A*	*B*	*C*	*D*	Average
1	1.79	1.79	1.80	1.83	1.80
2	1.80	1.80	1.80	1.82	1.81
3	1.75	1.76	1.79	1.80	1.78
4	1.73	1.74	1.74	1.74	1.74
5	1.68	1.68	1.68	1.68	1.68
6	1.52	1.52	1.52	1.53	1.52
7	1.43	1.42	1.43	1.45	1.43
8	1.28	1.26	1.27	1.27	1.27
9	1.12	1.12	1.13	1.11	1.12
10	0.98	0.97	0.96	0.98	0.97
11	0.83	0.81	0.82	0.84	0.82
12	0.69	0.68	0.67	0.70	0.68
13	0.57	0.57	0.57	0.54	0.56
14	0.46	0.47	0.46	0.43	0.46
15	0.34	0.34	0.32	0.32	0.33
16	0.26	0.25	0.25	0.24	0.25
17	0.14	0.15	0.15	0.15	0.15
18	0.08	0.09	0.08	0.10	0.09
19	0.04	0.05	0.04	0.06	0.05
20	0.02	0.02	0.03	0.01	0.02

Table II. *Reflection density readings on a neutral gray tablet and on half-tone prints reproduced from it.*

Step No.	Original tablet		120-line half-tone		60-line half-tone	
Observer	*A*	*B*	*A*	*B*	*A*	*B*
1	1.54	1.55	1.16	1.14	1.18	1.18
2	1.30	1.30	1.07	1.06	0.90	0.90
3	1.10	1.10	0.83	0.81	0.72	0.70
4	0.92	0.92	0.65	0.63	0.59	0.59
5	0.75	0.74	0.72	0.71	0.64	0.64
6	0.47	0.48	0.52	0.50	0.44	0.41
7	0.26	0.26	0.30	0.29	0.17	0.16
8	0.00	0.00	0.07	0.06	0.04	0.04



A

B

Fig. 3A. 120-line half-tone; B. 60-line half-tone.

Figures are also given for the reflection density readings made on the proofs from two half-tones, one 120-line, the other 60-line, of this same test object. These half-tones are printed herewith (Fig. 3). The values given in the table are single readings made by two observers and show that the marked texture of half-tone reproductions offers no difficulty in measurement with this instrument. These readings alone show the nature of the failure of half-tone reproduction, since the values would be the same as for the original if the reproduction were perfect. These data are merely to illustrate the performance of the instrument.

Factors Affecting the Measured Value of Reflection Density

The measurement of reflecting power or reflection density is affected by a number of conditions. There are even more factors to be considered than in the case of transmission measurements. Insofar as the author is aware, these factors have not been stated previously, so it may be timely to set forth now the funda-

mentals for the precise measurement of reflection density. These facts may be helpful to those who have built such instruments in the past and to those interested in other phases of reflection measurement.

When photographic paper is concerned, these factors are, in order of importance: (1) Incident angle and cone angle of illumination. (2) Viewing angle and cone angle collected. (3) Flare, when permitted, due to light areas surrounding that measured. This is one form of instrumental error. (4) Reflecting power of the paper stock. (5) Illumination conditions behind the paper. (6) Spectral quality of illumination. (7) High magnification, in the case of some rough-surfaced papers. (8) Orientation of the paper in its plane, with respect to the incident light, in the case of some papers.

(1), (2) The illumination on the sample should be at 45° to the normal and the sample viewed normally, according to recognized practice. This convention is observed in the present instrument. It was found that errors greater than two degrees in either illuminating or viewing angles caused noticeable differences in measured density values. As for the cone angles concerned, the illumination is from a concentrated filament lamp, so that the cone angle is small. The collected cone angle is also quite small. The effect of using large cone angles has been investigated by Davies.[4] In the present instrument the only other illumination which can reach the sample is that reflected from the operator's clothing, which has no appreciable effect.

(3) A light surround may give trouble in measurement, due to the flare it causes in the optical system. In the present instrument this is prevented by masking off the surround with a matte black surface and by cutting down the illuminating beam to a size slightly larger than that required.

(4) Papers differ slightly from each other in reflecting power of the stock. It is customary to give reflection density values regarding that of the stock as zero. The question has been raised as to whether the stock chosen for zero setting should be developed and fixed out, or merely fixed out. The two read the same, except when fog occurs, and fog is rare on photographic paper. Since it is desirable to show fog when present by the H and D curve, it is the practice here to use fixed-out but undeveloped stock for setting zero.

(5) Measured density values for deposits on single or light weight paper stocks depend noticeably on the reflecting power of the clamp surface behind the sample. The decision regarding this surface was based on the following facts: The contrast of single and light weight prints is slightly altered, that of double weight prints is unaffected by background conditions. Prints are usually viewed under one of three conditions: (1) unmounted and held away from other objects; (2) mounted, usually on light toned mounts; (3) mounted in albums. In the first case, the illumination on the back of the print is very much smaller than that on the face, so that the background may be regarded as dark. Prints on light mounts have effectively a light background. Prints so mounted are almost always on double weight paper, which does not show the effect considered. Such prints need not, therefore, be considered. Prints mounted in albums have in most cases a dark background. It is evident, therefore, that the sample should have a dark background for purposes of measurement, to represent practice. Moreover, a more permanent dark surface can be obtained for the sample clamp, as opposed to a white surface. The actual reflecting power of the surface is immaterial, provided it is below about 10 percent. This background condition is consistent with previous instruments in this laboratory.

(6) When the developed deposit is perceptibly colored its measured density will depend on the quality of illumination. A tungsten lamp at about 3000°K is used in the present instrument and there are no filters anywhere in the optical system.

(7) In the case of high densities on some rough surface papers, their appearance on close inspection is that of many bright points on a dark field. The tendency in photometrically matching a field of this kind, aside from the difficulty, is to match against the background, rather than to integrate. For example, a sample of carbon-surfaced paper had a density of 1.27 when viewed at 25 cm and on being magnified $\times 6.0$ the measured value became 1.38. With the present instrument the surface itself is not viewed but the light from it is integrated and a

uniform field is presented to the observer. Measurements on rough-surfaced paper with this system agree closely with those made viewing the paper surface at 25 cm, which is a suitable distance for viewing prints.

(8) It has been found by Sanders and Owen,[12] of Kodak Limited, England, that the measured value of reflection density of a photographic deposit on some paper bases varies with the orientation of the paper with respect to the incident light. This effect seems to arise from reflection from the paper fibers and is small for most photographic papers in which the fibers are masked by sizing and emulsion. For papers that exhibit the effect appreciably, the convention has been adopted here of placing the sample so that the angle between fiber direction and illumination azimuth is 45°.

Consideration of these factors will explain disagreements which sometimes occur between reflection densitometers of different types. It is apparent from these considerations that the precise measurement of reflection density is affected by more factors than is the measurement of transmission density.

[12] T. D. Sanders and R. E. Owen, *The Dependence of the Reflection Density of a Photographic Paper on the Orientation of the Paper with Respect to the Incident Light*, Phot. J. **73**, 398–402 (1933).

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C. Dunbar, *Reflection Factors of Photographic Papers*, Trans. Opt. Soc. Am. **32**, 184–96 (1930–31).

F. Formstecher, *The Measurement of Reflection Density*, Phot. Ind. **24**, 1301–2 (1926).

G. Schwarz, *Photo-Electric Measurement of Photographic Densities*, Phot. Korr. **67**, 63–67 (1931).

The Construction and Use of a Pfund Parallel Plate Refractometer

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(Received October 30, 1933)

INTRODUCTION

IN 1931, A. H. Pfund[1] outlined a new method of measuring the refractive index of liquids. Briefly, his method is as follows:

The liquids to be studied are placed upon a horizontally mounted plane parallel plate of glass of high refractive index whose lower surface is coated with white enamel. A brilliant point of light is projected from above through the liquid and the glass onto this lower painted surface of the glass. The index of refraction is then determined by measuring the diameter of the ring of light produced by total reflection at the glass-liquid interface.

REASON FOR THIS INVESTIGATION

The novelty and simplicity of this method and the fact that, by its use, a study might be made of the time rate of change of index of refraction of the drying oils of the paint industry and the varnishes and lacquers in common use, suggested the desirability of constructing and testing such an instrument.

APPARATUS

Fig. 1 shows diagrammatically the refractometer as actually used in this investigation. In order to avoid the confusing effects of specular reflection, the observing microscope was set so that its vertical plane was at right angles to the vertical plane through the light source and optical train. For the sake of simplicity, this arrangement is not shown in the drawing.

Two plane parallel glass plates approximately 10 cm square were used, one of which, 5.957 mm thick, had an index of refraction of 1.521 and the other, 5.141 mm thick, had an index of refraction of 1.619. Since the largest ring that could be seen with sufficient clarity to measure accurately, had a diameter of slightly less than sixty millimeters, the plates used limited the apparatus to the measurement of liquids having indices of refraction less than the following limits: 1.521 glass limit was 1.413; 1.619 glass limit was 1.523.

Since this apparatus is primarily intended as a means of determining the time rate of change of index of refraction of the liquids tested, it was first tried out on liquids having well-known indices of refraction and then applied to the solvents, "drying" oils and the varnishes and lacquers of the industry. The results follow in the next section in Figs. 2, 3 and 4.

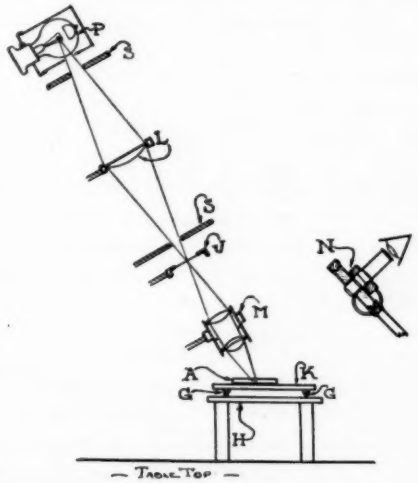

FIG. 1. Diagrammatic sketch of the Pfund's parallel plate refractometer. *P*, a Pointolite lamp; *P*, *L*, *J*, *M*, the optical train; *L*, a condensing lens; *J*, a smoked brass diaphragm with a small central needle hole; *M*, a short focus lens, highly corrected; *A*, the refractometer plate; *S*, an opaque screen to shield the plate from any extraneous light; *G*, *H*, *K*, supporting and levelling equipment; *N*, the observing microscope.

All of the tests were conducted in a room about fifteen feet square, having no windows and little ventilation. The liquids were open to the air of the room and no attempt was made to

[1] A. H. Pfund, J. O. S. A. **21**, 182–186 (1931).

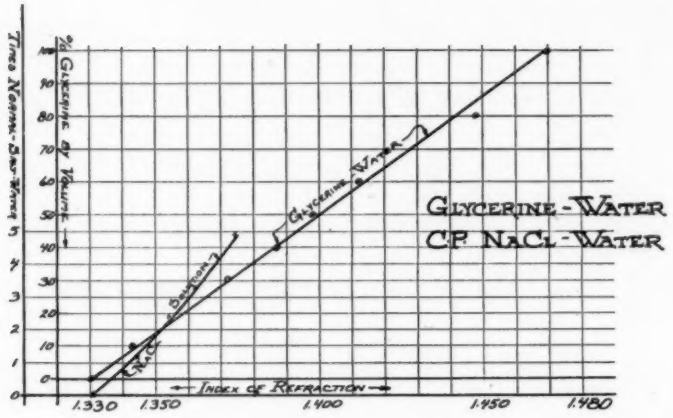

FIG. 2. The change of index of refraction with concentration.

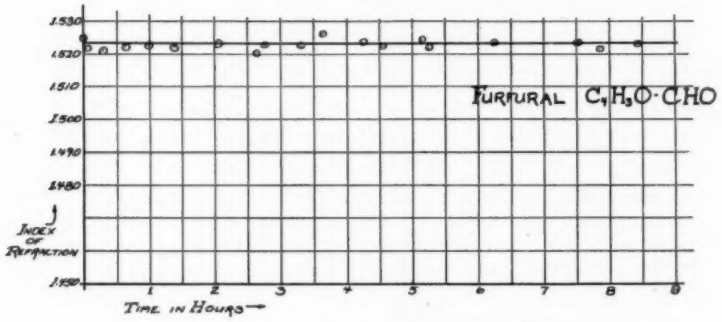

FIG. 3. Time rate of change of index of refraction.

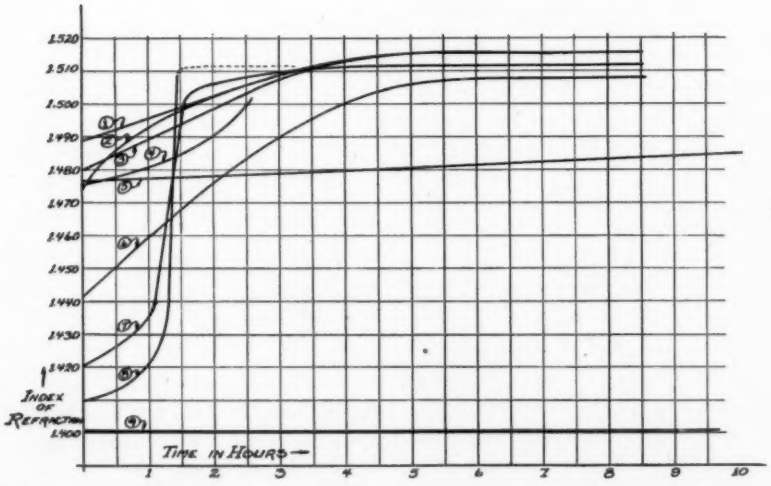

FIG. 4. Comparison of time rate of change of various substances: (1) Lowe Neptunite Spar Varnish; (2) Elkay Clear Lacquer; (3) Dupont Standard Spar Varnish; (4) clear turpentine; (5) boiled linseed oil; (6) Rogers Clear Brushing Lacquer; (7) normal Egyptian Lacquer; (8) dilute Egyptian Lacquer; (9) amyl acetate.

accelerate or retard their normal evaporation rate. The average room temperature is given at the end of the discussion of the particular substance.

Discussion of Graphical Results

Fig. 2 gives in graphic form the variation of index of refraction with concentration for glycerine and water and also for chemically pure NaCl and water. The glycerine and water curve appears to be a straight line and may indicate that negligible ionization takes place. The salt water curve, however, shows a slight curvature of about the sort that might be expected to result from the effects of ionization. These tests were made at an average room temperature of 24.0°C.

Fig. 3 shows the time rate of change of index of refraction for furfural, secured from the Chemistry Department here. It was hoped that some of the complex structural changes that are thought to take place within the substance as it is allowed to remain exposed to the air would show up in the curve of time rate of change of index of refraction. Such changes as may have occurred were evidently less than the experimental errors as the trend of the curve is definitely linear. The average room temperature was 33.0°C.

Fig. 4 is a composite of curves of time rate of change of index of refraction for the liquids listed in Table I.

The diluted Egyptian Lacquer evaporated so rapidly and left so thin a film that it was extremely difficult to determine accurately the course of the entire curve. The dotted portion represents an extrapolation based upon the results for undiluted lacquer, with such allowances as were thought necessary for the additional dilution.

Table I.

Liquid	Average room temperature
Amyl acetate	27.0°C
Linseed oil "boiled"	32.0
Rogers Clear Brushing Lacquer	26.0
Turpentine (commercial water white)	22.0
Egyptian Lacquer, normal and diluted	27.5
Dupont Spar Varnish	31.5
Elkay Clear Lacquer	31.5
Lowe Neptunite Spar Varnish	26.5

General form of the curves obtained

The form of the curve of time rate of change of index of refraction for pure lacquers may, from theoretical considerations, be expected to show a gradual rise characteristic of the period during which the concentration gradient is being established, a straight portion indicative of steady conditions and a final slumping off to the definite value of index of refraction for the solute itself. Such a curve is in fact actually obtained in the case of Egyptian Lacquer (see Fig. 4).

The curve of time rate of change of index of refraction for varnishes largely composed of linseed oil may equally probably be expected to show a very gradual rise and slow flattening off without any very definite transition points. In a very general way, this may be due to the fact that "drying" of linseed oil is really oxidation and is very slow compared to the evaporation of the lacquer solvent and also the oxidized linseed oil differs only slightly in index of refraction from the liquid before oxidation. Characteristic of this type of curve is that for Lowe Brothers Neptunite Spar Varnish (see Fig. 4).

Naturally, many commercial varnishes are combinations of these types and so any variation or combination of these curves may be expected. All that may be learned from the form of the curve is an indication of the type of drying process taking place. In some cases, this may be all that is desired and may not be readily determinable in any other convenient way.

Accuracy of the results

From a study of the equation relating index of refraction to the constants of the apparatus, as well as by comparing the indices of refraction obtained for a given liquid with the accepted values, the most probable error for the instrument was 0.5 percent. This value seemed fairly constant over the range of the apparatus from distilled water 1.333 to furfural 1.523.

General Conclusions

The apparatus as used proved to be a quite rapid and simple method of determining the

index of refraction of liquids within a range up to 1.523 with an over-all accuracy of about 0.5 percent. Greater accuracy could undoubtedly be attained by using a plate of glass still more precisely plane parallel, say to within a few wavelengths of sodium light, and of index of refraction in excess of 1.619, and by employing a micrometer microscope of magnification less than one and of greater light gathering power than the eye, so that the image of the ring formed would appear brighter than to the unaided eye.

By far the most valuable feature of the work for commercial purposes, however, is its ability to trace the time rate of change of index of refraction of such liquids as varnishes and lacquers and thus to assist the paint industry to maintain the quality and uniformity of its products.